

Original Articles

Multicriteria decision analysis framework for hydrological decision support using environmental flow components



Daniel Butchart-Kuhlmann*, Sven Kralisch, Melanie Fleischer, Markus Meinhardt, Alexander Brenning

Department of Geography, Friedrich Schiller University Jena, Loebdergraben 32, 07743 Jena, Germany

ARTICLE INFO

Keywords:

Hydrology
Climate change
Decision support systems
Indicators of hydrologic alteration
Environmental flow components
Multicriteria decision analysis

ABSTRACT

Assessing the quantity and quality of water available in water stressed environments under various potential climate and land-use changes is necessary for good water and environmental resources management and governance. We present a novel approach with which to assess water quantity in the Luangina basin, a subbasin of the upper Zambezi River, using existing results of hydrological modelling based on climate change scenarios, hydrological indicators, and multicriteria decision analysis. Flexible input criteria and open-source software are used to the greatest degree possible. Scenarios are represented through a combination of model input data and parameter settings in the hydrological model, and preferences are represented through criteria weighting in the multicriteria decision analysis. The resulting methodology, combining hydrological indicators with MCDA, is thus adaptable, in terms of both application platform and subject matter. The method results were largely as expected. When a decision maker expressed a preference for wetter conditions, the RCP 4.5 scenarios were generally deemed most suitable, and thus ranked highest. When drier conditions were preferred, the RCP 8.5 scenarios, resulting in less streamflow and less frequent flood events, were ranked highest. Validation of the results is not possible, due to the methodologically exploratory nature of the research being undertaken. The promising results do, however, allow for further research that builds upon the work undertaken here, to be envisaged.

1. Introduction

Assessing the amount of water available in water-stressed environments under various potential climate and land-use changes is necessary for good water and environmental resources management and governance. On the whole, Africa is viewed with high confidence as being subjected to increased stress on water availability, in particular in areas already affected by water stress today (Niang et al., 2014). More specifically, southern Africa is projected to become drier with climate change (Serdeczny et al., 2016). Kling et al. (2014) well summarize the results of existing models of the upper Zambezi in particular, concluding that, although uncertainty exists, the consensus of existing research results is that runoff is likely to decrease, perhaps by up to 40% by 2050, due to a combination of decreased rainfall and increased temperature. In view of this, it is key to allow for adequate natural resources planning. The present research aims to contribute to work on water availability in the upper Zambezi, and so aid stakeholders in making critical planning decisions as to how water is managed in the future.

1.1. State of the art

A decision support system (DSS) can be defined as a software system that provides five functionalities: a database and processing environment; a knowledge and information system; modelling analysis frameworks; socioeconomic analysis; and a communication framework (e.g. public web platform) (GWP, 2013). According to Georgakakos (2006), “the role of DSS is to leverage current scientific and technological advances in developing and evaluating specific policy options for possible adoption in” water resources management.

Currently, the Integrated Land Management System (ILMS) software package developed and provided by FSU Jena covers all of the functionalities listed above, to varying degrees, apart from that of socioeconomic analysis. The database and processing environment are provided through the use of the SASSCAL Information System (SASSCAL-IS) platform. The IS also provides a basis for the knowledge and information system category, as well as the communication framework. The modelling analysis framework functionality is covered in ILMS by the various J2000 hydrological models available. What remains undealt

* Corresponding author.

E-mail address: daniel.butchart-kuhlmann@uni-jena.de (D. Butchart-Kuhlmann).

with, at least in the SASSCAL-IS context, is the development and support of a socioeconomic analysis functionality, which is out of the scope of the current, hydrologically focussed, research, but which we aim to develop on the basis of the research presented here.

In terms of African, and in particular southern African, indicators of hydrologic alteration analysis, some previous research does exist. Of specific interest here is the work by [Martínez-Capel et al. \(2016\)](#), who undertook an indicators of hydrological alteration (IHA)/environmental flow component (EFC) analysis on the Zambezi-Chobe River in Namibia. In contrast to that study, however, where the environmental flow component output was used as input to the WEAP21 hydrological decision support system, the present research, by applying the IHAs/EFCs to a multicriteria decision analysis, uses environmental flow components differently.

Some research applying IHAs/EFCs as input for multicriteria decision analysis has already been undertaken. [Martin et al. \(2015\)](#), using the Ecological Limits of Hydrologic Alteration (ELOHA) hydrological assessment indicators set, used the EFCs as a basis for the evaluation of social preferences into watershed management planning exercises. [Porse et al. \(2015\)](#) use EFCs derived from the indicators of hydrologic alteration framework to compare different potential reservoir storage possibilities, bearing in mind the different objectives of different user groups. As such, expanding the interpretation of the EFCs to a wider scope, including but not limited to the original ecological scope, as is planned in the SASSCAL-DSS, appears to be a feasible goal.

With regards to the application of the Preference Ranking Organization Method for Enrichment of Evaluations, or Promethee, method, used here, in water resources management, [Bezhadian et al. \(2010\)](#) state that 14.4% of all papers published that made use of the Promethee method in some way, up to the point of the review, focussed on the topic of “Hydrology and Water Management”. This topic denotes “sustainable water resources planning, water management strategies assessment, and irrigation planning”, corresponding to the sphere of the research presented here.

Use of the Promethee MCDA method in combination with hydrological modelling data is thus a feasible combination, as is the use of the IHA/EFC framework with MCDA. Where the approach presented here innovates, however, is in the use of the combination of hydrological modelling results, hydrological indicators, and MCDA to evaluate the suitability of different climate change scenarios for different stakeholder groups (albeit hypothetical ones).

1.2. Objectives

So as to enable improved data collection and analysis regarding issues such as water vulnerability, and a myriad of other related topics, as well as to enhance organisational cooperation of researchers, governance, and stakeholders within and regarding the region, the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) initiative was undertaken.

One goal of the SASSCAL project, and the objective of the research presented here, is to develop and provide an integrated decision support system with which decision makers (DMs) within a given catchment can obtain objective information regarding potential changes in water flow quantity and timing. The results of this research thus far are presented here.

2. Materials and methods

The hydrological decision support system developed here uses output from existing, validated hydrological models as the basis of the calculation of a range of hydrological indicators based upon indicators of hydrologic alteration and environmental flow components calculated for a historic time series (pre-impact), and a set of model simulations based upon a selection of climate change scenarios (post-impact). These indicators, obtained using the Indicators of Hydrologic Alteration

software package, a process developed, documented, and maintained by [The Nature Conservancy \(2009\)](#), are then used as input for a multicriteria decision analysis undertaken using an open source MCDA software package, *diviz*. The results of these analyses will provide decision makers with an indication as to how various hydrological indicators within a catchment may be altered under different future scenarios, as well as providing a ranking of how each scenario best suits different DM preferences. A more detailed description of the method and its various components applied here follows.

2.1. Methodological overview

The work presented in this paper is based on the results of a catchment-scale hydrological model of the Luanganga catchment of the Zambezi River by [Meinhardt \(2017\)](#), involving model calibration and validation, and subsequent modelling of the Luanganga using several sets of climate projection data for the study region. The results of this prior research form the basis of the present research, as they were then used as input with which to obtain a set of environmental indicators. These indicators were obtained using the Indicators of Hydrological Alteration software. This program aims to provide the user with a detailed breakdown of how streamflow dynamics are altered between a pre- and post-impact period. Although usually applied for projects such as dam construction, there is no great issue with using post-impact data consisting of streamflow generated under a specific climate change scenario. The final step of the process involves using a set of indicators output from the IHA program as input to the Promethee II MCDA in the *diviz* modelling environment. These indicators fill the role of the criteria to be assessed in the MCDA, under a selection of scenarios and preference values. What follows is an overview of the concepts used.

2.2. Summary of catchment and hydrological data used

The data that the present research is based on consist of the results of the J2000 hydrological model applied using climate forcing data from four different downscaled Representative Concentration Pathway (RCP) datasets, consisting of two scenarios from two models (ECHAM 4.5/8.5, and EC-EARTH 4.5/8.5). A flood component was developed specifically for use in the Luanganga catchment, an area subject to seasonal flooding. For full details of the hydrological model used, see [Meinhardt \(2017\)](#). For further information on the J2000 model and applications thereof, including in southern Africa, see, for example, [Krause \(2001, 2002\)](#), [Fischer et al. \(2009\)](#), and [Helmschrot et al. \(2014\)](#).

The majority of the Luanganga subbasin is located in Angola, and the rest in Zambia ([Fig. 1](#)). Since it is one of the smallest catchments in the Zambezi Basin, flooding often occurs shortly after heavy rainfall ([World Bank, 2010](#)). Due to its relatively remote location, there is very little human development and human influence upon the river, with no dams or hydropower plants, or plans for any, along the river ([World Bank, 2010](#)). The low levels of development and human impact on the river thus provide suitably ‘natural’ streamflow values, and thus too, EFC values, with which to undertake an MCDA that is not subject to much, if any, uncertainty due to human factors in the area itself.

2.3. Indicators

Indicators of hydrologic alteration were used here as they are shown by [Olden and Poff \(2003\)](#) to be effective in representing a wide range of flow regime information without using an overly large selection of indicators, stating that IHAs “capture the majority of the information provided by the population of indices available to researchers”. Despite indications that fewer indicators could be used, the present study, due to its aim of providing a generally applicable methodology, rather than geographically specific results, applied the range of IHAs/EFCs.

Use of the IHA framework has a number of other advantages.

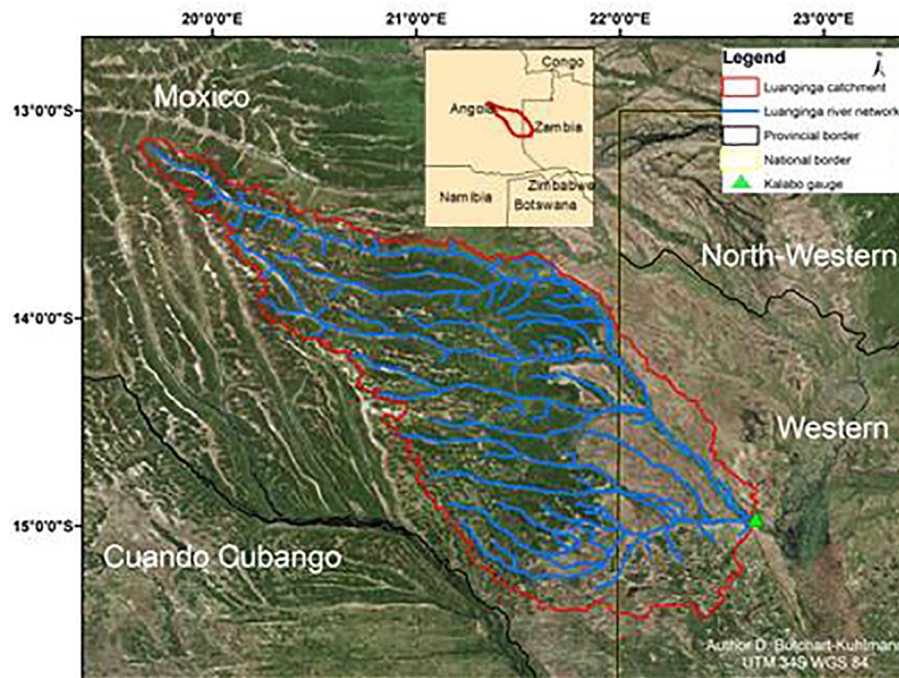


Fig. 1. Map of the Luanginga catchment and gauging point used in the hydrological model (adapted from Meinhardt (2017)).

Indeed, due to the numerous studies undertaken (Tharme, 2003), the IHA framework has evolved and improved through researcher feedback and communication with the developers. Furthermore, the fact that IHAs have been used so often means that a degree of comparability between studies is possible, using the common statistical and indicator basis provided by the IHAs. As such, although other indicators exist (e.g. Henriksen et al., 2006; Poff et al., 2010; Martin et al., 2015) with which to undertake an assessment of watershed health, the IHA framework was chosen due to ease-of-use, widespread use, and sufficient complexity, so as to be somewhat representative of real-world conditions.

A further key element justifying the choice of the IHA framework is the existence of the IHA based environmental flow components. EFCs permit ecological conclusions to be drawn based upon purely hydrological output data/results, in the form of the IHAs. Poff and Zimmerman (2010) succinctly summarize the case for EFCs, stating: “[n]umerous case studies (and expert knowledge) provide the foundation of our scientific understanding that many types of flow alteration (e.g. magnitude, frequency, and timing) induce a variety of ecological responses”. A general overview of each EFC and how it is deemed to influence a riverine ecosystem is shown in Table 1 (adapted from The Nature Conservancy (2009)).

Overall, and quite expectedly, it appears to be that the greater the alterations in streamflow regime in a catchment, the greater the ecological impacts will be, compared to a pre-management condition. In particular, alterations in streamflow magnitude (e.g. floods and droughts) tend to have a very strong impact on the surrounding ecology (see Poff and Zimmerman, 2010). Of course, ecological changes are likely due not just to a single hydrological alteration, but rather, a combination of magnitude, duration, frequency, and timing (Tharme, 2003). However, from their literature review, Poff and Zimmerman conclude that the main IHA driver in terms of ecological impact appeared to be flow magnitude.

In the present methodology, once generated, through use of hydrological modelling results in combination with the IHA software, the EFC values are then used as the performance values and criteria in the multicriteria decision analysis. As such, it is assumed that, to use the results, the user will simply need to determine how each EFC influences

the non-hydrological aspect upon which they are focussed, if this is the case. Furthermore, in such a way, EFCs are deemed to be reasonably suitable to form the basis of further socioeconomic analysis (an aspect missing from the SASSCAL-DSS thus far) by acting as a proxy for other, non-hydrological, but related, indicators, analogous or combined with, for example, ecosystem services/functions (see Arthington et al., 2006).

It should be noted that IHA analysis has traditionally consisted of using a two-period dataset composed of pre- and post-alteration time series, in previous studies often separated by the construction of a dam on the river in question (Malingi and Marsh, 2002; Magilligan and Nislow, 2005; Yang et al., 2008; Sojka et al., 2016). However, building on the work of, amongst others, Dyer et al. (2014) and Stagl and Hattermann (2016), the present analysis provides as ‘post-alteration’ data a selection of modelled time-series based upon different climate scenarios.

2.4. Multicriteria decision analysis and Promethee

Multicriteria decision analysis is defined by Figueira et al. (2005) as “the approach of explicitly taking into account the pros and the cons of a plurality of points of view.” A range of different MCDA methods exists, broadly summarized into three groups: the full aggregation approach, or American school; the outranking approach, or French school; and the goal approach, also known as multiple-objective decision-making (Ishizaka and Nemery, 2013). Sadok et al. (2008), drawing from Zanakakis et al. (1998) and Figueira et al. (2005) describe MCDA as aiming “to develop methods and tools to assist with decision-making, particularly in terms of the choice, ranking or sorting of options (i.e., alternatives, solutions, courses of action, etc.), in the presences of multiple and often conflicting criteria.” Sadok further deconstructs the MCDA methodology, using Roy (1985) and Maystre et al. (1994), describing it as “a non-linear recursive process including four main steps: (i) structuring the decision problem, (ii) articulating and modelling the preferences, (iii) aggregating the alternative evaluations (preferences), and (iv) making recommendations.”

The MCDA technique used here is the Promethee technique. Promethee is an MCDA method belonging to the French school, developed by Brans, that aims to outrank different alternatives. It is based

Table 1

The environmental flow components and examples of influence upon an ecosystem. Adapted from [The Nature Conservancy \(2009\)](#). MCDA abbreviation added.

Environmental Flow Component (EFC) – 34 parameters			
EFC Type	Hydrologic Parameters	MCDA abbreviation	Ecosystem Influence
1. Monthly low flows	Mean or median values of low flows during each calendar month – January	October Min	Provide adequate habitat for aquatic organisms
	Mean or median values of low flows during each calendar month – February	November Min	Maintain suitable water temperatures, dissolved oxygen, and water chemistry
	Mean or median values of low flows during each calendar month – March	December Min	Maintain water table levels in floodplain, soil moisture for plants
	Mean or median values of low flows during each calendar month – April	January Min	Provide drinking water for terrestrial animals
	Mean or median values of low flows during each calendar month – May	February Min	Keep fish and amphibian eggs suspended
	Mean or median values of low flows during each calendar month – June	March Min	Enable fish to move to feeding and spawning areas
	Mean or median values of low flows during each calendar month – July	April Min	Support hyporheic organisms (living in saturated sediments)
	Mean or median values of low flows during each calendar month – August	May Min	
	Mean or median values of low flows during each calendar month – September	June Min	
	Mean or median values of low flows during each calendar month – October	July Min	
	Mean or median values of low flows during each calendar month – November	August Min	
	Mean or median values of low flows during each calendar month – December	September Min	
2. Extreme low flows	Frequency of extreme low flows during each water year or season	ELP	Enable recruitment of certain floodplain species
	Mean or medium values of extreme low flow event – Duration (days)	ELD	Purge invasive, introduced species from aquatic and riparian communities
	Mean or medium values of extreme low flow event – Peak flow (minimum flow during event)	ELT	Concentrate prey into limited areas to benefit predators
	Mean or medium values of extreme low flow event – Timing (Julian date of peak flow)	ELF	
3. High flow pulses	Frequency of high flow pulses during each water year or season	HFP	Shape physical character of river channel, including pools, riffles
	Mean or median values of high flow pulse event – Duration (days)	HFD	Determine size of streambed substrates (sand, gravel, cobble)
	Mean or median values of high flow pulse event – Peak flow (maximum flow during event)	HFT	Prevent riparian vegetation from encroaching into channel
	Mean or median values of high flow pulse event – Timing (Julian date of peak flow)	HFF	Restore normal water quality conditions after prolonged low flows, flushing away waste products and pollutants
	Mean or median values of high flow pulse event – Rise and fall rates	HFRR/HFFR	Aerate eggs in spawning gravels, prevent siltation
			Maintain suitable salinity conditions in estuaries
4. Small floods	Frequency of small floods during each water year or season	SFP	Provide migration and spawning cues for fish
	Mean or median values of small flood event – Duration (days)	SFD	Trigger new phase in life cycle (i.e. insects)
	Mean or median values of small flood event – Peak flow (maximum flow during event)	SFT	Enable fish to spawn in floodplain, provide nursery area for juvenile fish
	Mean or median values of small flood event – Timing (Julian date of peak flow)	SFF	Provide new feeding opportunities for fish, waterfowl
	Mean or median values of small flood event – Rise and fall rates	SFRR/SFFR	Recharge floodplain water table
5. Large floods	Frequency of large floods during each water year or season	LFP	Maintain diversity in floodplain forest types through prolonged inundation (i.e. different plant species have different tolerances)
	Mean or median values of large flood event – Duration (days)	LFD	Control distribution and abundance of plants on floodplain
	Mean or median values of large flood event – Peak flow (maximum flow during event)	LFT	Deposit nutrients on floodplain
	Mean or median values of large flood event – Timing (Julian date of peak flow)	LFF	Maintain balance of species in aquatic and riparian communities
	Mean or median values of large flood event – Rise and fall rates	LFRR/LFFR	Create sites for recruitment of colonizing plants
			Shape physical habitats of floodplain

upon the pairwise comparison of the criteria, using user specified weighting and threshold values, and provides the user with a simple ranking (or rankings, depending on which variation one uses) of the alternatives given the DM weights.

To obtain the preference value, or outright ranking, of one alternative over another, as required for Promethee II, the net flow of an alternative must be calculated. The net flow of an alternative is the balance between the positive and negative outranking flows. The

positive flow of an alternative represents the strength of an alternative, providing a value for the degree to which it outranks others, and should be maximized. The negative flow of an alternative represents the weaknesses of an alternative, or the degree to which it is outranked by other alternatives, and should be minimized if the alternative is to perform well (De Smet and Lidouh, 2013). Overall, the greater an alternative's net flow, the better the alternative is for the DM in question (Francq, 2004). In contrast, Promethee I consists of providing two sets of rankings, defined by the positive and negative flows of the alternative's performance compared to the other alternatives assessed. Promethee II was selected here so as to provide the DM with a clear set of information in the form of a simple best-to-worst ranking.

Six functions can be used for applying the Promethee method. This analysis uses the linear function, requiring the application of only a preference threshold and one of two preference directions (max, min) depending on the parameter and hypothetical user group. Indeed, as Turcksin et al. (2011) state, "for quantitative assessment, the [Promethee] guidelines advise to apply a linear preference function". The preference values used were derived either from the literature, or were set based upon hypothetical preferences. The values used and the output obtained will be presented further on.

For a succinct summary of the Promethee process, see Alvarez-Guerra et al. (2010). For a more in-depth presentation and discussions of the method and the various function types available, see, for example, Brans and Vincke (1985), Brans et al. (1986), and De Keyser and Peeters (1996).

On a terminological note, although MCDAs commonly analyse a degree of DM *preference* for a given scenario, in this work, the MCDA does not assess DM preference, as a DM does not have any choice as to which scenario the catchment will actually be subject too. Instead, the present MCDA assesses the *suitability* of a scenario to a DMs preferred indicator values. As such, the results of the MCDA are assessed in terms of suitability (highest ranked being most suitable, and lowest, least suitable).

2.5. Application

The multicriteria decision analysis was implemented using the diviz software package, developed by the Decision Deck Consortium, whose goal is "to collaboratively develop open-source software tools implementing MCDA techniques" aimed at practitioners, teachers, and researchers (Bigaret and Meyer, 2015). By combining input data provided in the form of an XMCD file, an extension of the XML format specifically designed for MCDA purposes, with open-source analyses hosted on the diviz server, diviz allows a range of users to design and apply various MCDA techniques and analyses. This configuration means users can undertake these analyses without having to write the code themselves, as well as providing a format and platform that is easy to share and understand between users. Overall, diviz can be summarized as "an open source Java client and server for designing, executing and sharing MCDA methods, via the composition of XMCD web services" (Ros, 2011).

An overview of how the MCDA using the Promethee method was applied to EFCs is shown in Fig. 2. Each element of the MCDA analysis was defined within an XMCD file (DMs, Alternatives, Criteria and criteria units, and criteria weights), which were then used as input to the various modules required for the Promethee analysis in diviz.

The weights were obtained by first ranking each criteria on a scale of 0–5, zero being no preference, one being low preference, and 5 high preference. Such a scale may, for example, be used when eliciting weights from decision makers. These values were then converted to a scale from 0 to 1, so as to conform with the diviz Promethee input requirements.

Despite a key characteristic of an MCDA being the elicitation of criteria and weights from stakeholders, either directly or indirectly (Keeney, 1977; Braziunas, 2012; in Convertino et al. (2013)), the MCDA

used here applied hypothetical weights, giving each criteria an equal weight, for a balanced DM group, and a variety of different weights, for three other groups. Indeed, research where weighting data is lacking is not uncommon, and thus, running an MCDA using hypothetical weights has precedent (e.g. Diaby et al., 2016). Further, hypothetical weights can be used in the case where analysts lack either time or resources to undertake a more in-depth weighting process (SINTEF, 2013; Alvarez-Guerra et al., 2010).

The hypothetical decision maker group values used here, in terms of weighting and preference directions (min/max) are defined as follows:

- **Balanced:** all criteria equal weight, minimize extremes (preferably no drought, no large floods).
- **Inhabitants:** preference to maximize monthly flow, high flow pulses, and small floods. No preference for extreme low flows and large floods, which should be minimized.
- **Mad Max:** low preference to minimize some monthly flow. High preference to maximize extreme low flow and high fall rates. No preference for all other EFCs, should be minimized.
- **Waterworld:** high preference to maximize all flow components except extreme low flow and fall rates, which should be minimized.

The use of hypothetical weights is permissible when eliciting weight values from decision maker groups is difficult or not possible (Alvarez-Guerra et al., 2010). Further, the "equal weights method" (Alvarez-Guerra et al., 2010), which entails distributing the weights to each criteria evenly, can be used when no real, decision maker defined preference/weighting data is available.

In the case of the balanced DM group, the MCDA analysis applied here applies equal weights to all criteria, and also to preference values within the criteria settings. The equal weighting effectively nullifies the value of each weight. However, the preference values, defined as the EFC values for the observed, historic dataset, mean that the MCDA is nonetheless evaluating which scenario performs best compared to the historic values, which can be taken, in the current catchment, to be an acceptable approximation of an undisturbed streamflow regime, as stated in the catchment description. Thus, the MCDA is comparing which scenario best compares to the natural state of the watershed, depending on DM group preferences.

3. Results

The results presented here consist of both methodological advances and the results of the application of these advances upon the data used. For each component of the MCDA framework developed here, results will be presented separately. This will then be followed by a broad discussion of issues that arose whilst the method was being developed, how the results may be interpreted and issues therewith, and how the method may be built upon, altered, or improved in the scope of future research.

3.1. Indicators of hydrologic alteration/environmental flow components

As stated above, the IHAs/EFCs are derived from the results of a hydrological model. In this case, these results originated from prior research undertaken by Meinhardt (2017). The first step in the methodology presented here entailed inputting the model run results to the IHA software. The initial measured hydrological time-series was used as the pre-impact dataset input for the indicators of hydrologic alteration calculation, and a set of model results from a 20-year period (2080–2100) was used as post-impact data input. In each case, the IHA results used were those obtained on the basis of the non-parametric setting (for detailed steps to be taken, and further clarification, see The Nature Conservancy, 2009). This was required to maintain data comparability, as well as to allow for the more extreme streamflow variability present in southern African rivers (see Jewitt et al., 1999; in

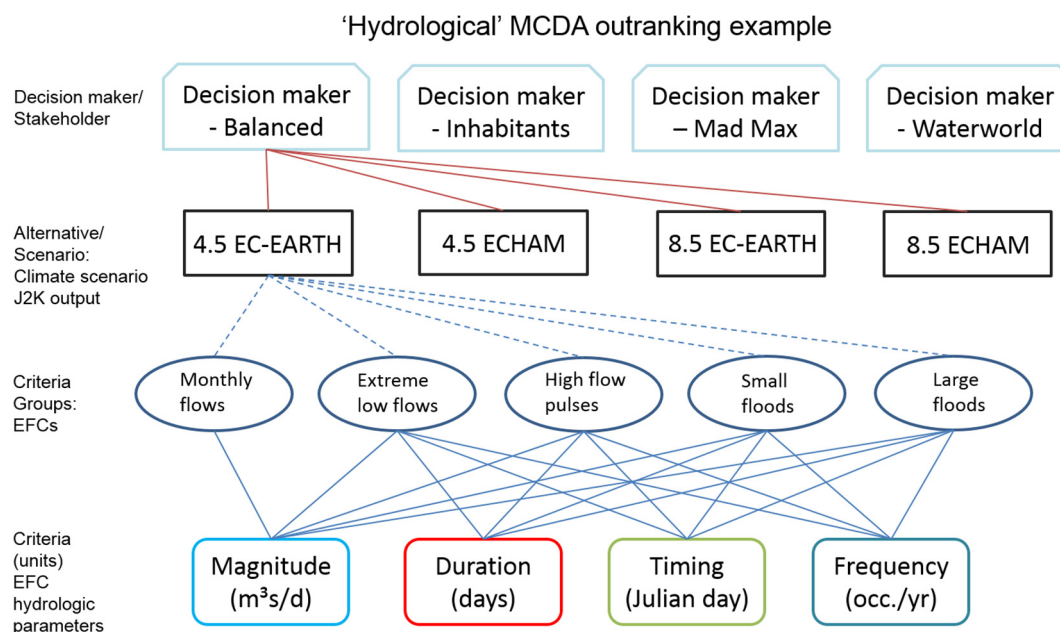


Fig. 2. Overview of MCDA structure applied in this analysis.

Schulze and Pike (2004)).

The different thresholds for flow components used in the indicators of hydrologic alteration analysis undertaken here were based upon various sources within the literature, in an attempt to replicate, at least to some degree, realistic interpretations of flow components and their corresponding environmental flow definitions. According to the World Bank (2010), so as to maintain the near-pristine condition of the Zambezi River upstream of the Kariba and Cahora Bassa dams, “the flow should never drop below the current low-flow levels in dry years, as estimated from statistical analysis, and the average annual flow should not drop below 60 percent of the natural average annual flow. This condition, is, in fact, a minimum flood constraint, as most of the annual run-off is produced during floods”. The limits set by the World Bank have previously been used in hydrological research on the Zambezi River. Indeed, Martínez-Capel et al. (2016) used various values for the Chobe-Zambezi River basin in the calibration of the environmental flow components algorithm for that watershed.

In view of the values for IHA parameters in the region present in the literature (e.g. World Bank, 2010; Martínez-Capel et al., 2016), the following thresholds were used in the current IHA analysis: small floods were classified as flooding between 61 m³·s and the 99th percentile of streamflow for the period (the hydrological year). Small floods are seen as being necessary, normal seasonal flooding, due to the gauge and catchment location in a floodplain. Large floods are floods with streamflow higher than the 99th percentile for the period. Extreme low flow was classified as a streamflow rate lower than the 10th percentile streamflow value for the period. High flow pulses were thus any streamflow values between the extreme low flow and small flood values. A detailed explanation of how the algorithms used to calculate each EFC function is presented in the IHA User's manual (The Nature Conservancy, 2009). The results of the IHA/EFC analysis are presented in Table 2, which also forms the basis of the performance table necessary for the subsequent MCDA.

As stated earlier, a degree of calibration was undertaken when generating the IHA/EFC values. This was done by comparing the extreme events documented during the observed period (1968–2013) and attempting to capture these events in the IHA/EFC analysis. As such, the final set of IHA output classifies major flood events in 2003, 2004, 2007, 2008, 2009, and 2014 (verified using the Dartmouth Flood Observatory global archives (Brakenridge, n.d.)), and a major drought in

1994–1995 (SARDC, 2015).

Viewing the results in Table 2, it is clear that the EFCs obtained using representative concentration pathway 4.5 data consist of more flooding, and, indeed, a more similar runoff cycle to the observed data. In contrast, the RCP 8.5 projections barely contain any large flooding at all. The EC-EARTH 8.5 scenario results show a particularly dry trend, with low small flood peak values, and no large flood events whatsoever.

3.2. Promethee MCDA

The data used in the multicriteria decision analysis are presented in Tables 2 and 3. The performance values used for each criteria in each scenario are the EFC values shown in Table 2. The weights and preference directions, defined by the hypothetical user groups described above, are presented in Table 3.

Overall, the MCDA results obtained are presented in Fig. 3. Where water availability is preferred, as well as when the weights are equally distributed, the EC-EARTH 4.5 scenario is most suitable. When the decision maker would prefer drier conditions with less flooding, the RCP 8.5 scenarios ranked best. An interesting outcome with regards to the balanced decision maker group is the preference of the ECHAM 8.5 scenario over the ECHAM 4.5 scenario. Apart from this anomaly, however, the results are broadly as one would expect with the weights provided.

4. Discussion

The results obtained permit the conclusion to be drawn that the multicriteria decision analysis framework presented and tested here appears to be a viable option for assessing the suitability of climate scenarios for different DM groups by taking into account different weighting options using EFCs based upon hydrological modelling results. However, the anomaly of the preference of the ECHAM 8.5 scenario over the ECHAM 4.5 scenario described in the results is a curious discrepancy, and should certainly be focussed upon in future work.

Overall, however, the findings of the IHA/EFC analysis section of the present work are consistent with the findings of other regionally focussed studies undertaken. Indeed, the results of the World Bank (2010) analysis on the estimated impact of climate change on the upper Zambezi by 2030 indicate a decrease of basin yield of –13%, under the

Table 2

Performance table generated using IHA/EFC values for the observed dataset and each modelled time series.

EFC	EFC indicator	Units	Observed	ECEARTH 4.5	ECHAM 4.5	ECEARTH 8.5	ECHAM 8.5
Monthly flows	October	m ³ /d	11.5	18	19	17	18
	November	m ³ /d	10.5	15	15.5	14	14
	December	m ³ /d	12	18	19	15	13
	January	m ³ /d	15.5	34	35	25	24
	February	m ³ /d	63.75	70.5	65	42.5	44.5
	March	m ³ /d	142	153	136	65	68
	April	m ³ /d	156.8	148.5	160	73	94.5
	May	m ³ /d	104	112	123	59	78
	June	m ³ /d	71	66.5	83.5	44.5	50.5
	July	m ³ /d	48.56	40	50	32	33
Extreme low flows	August	m ³ /d	31	27	33	24	24
	September	m ³ /d	18	22	23	20	20
	Extreme low peak	m ³ /d	7.75	4	7	6	8
	Extreme low duration	days	45.5	108	49	72	35
High flow pulses	Extreme low timing	Julian date	328.3	330	317	323	328
	Extreme low freq.	occ./yr	0.86	0.05	0.05	0.15	0.2
	High flow peak	m ³ /d	50	35	58	53.5	35
	High flow duration	days	50.5	3	124	90.5	1
Small floods	High flow timing	Julian date	98	353	79	89.5	1
	High flow frequency	occ./yr	0.05	0.05	0.05	0.2	0.05
	High flow rise rate	m ³ /d	2.58	17	0.53	0.44	23
	High flow fall rate	m ³ /d	0.42	1.67	0.25	0.29	6
	Small Flood peak	m ³ /d	183	184	154	100.5	112.5
Large floods	Small Flood duration	days	180	179.5	198	157.5	151.5
	Small Flood timing	Julian date	88	86.5	97	91	98.5
	Small Flood freq.	occ./yr	0.66	0.6	0.65	0.8	0.6
	Small Flood riserate	m ³ /d	3.04	2.29	1.82	1.41	1.63
	Small Flood fallrate	m ³ /d	1.04	1.20	0.97	0.65	0.80
Large floods	Large flood peak	m ³ /d	317	372	385.5		374
	Large flood duration	days	215	208	209		192
	Large flood timing	Julian date	76	86	89		81
	Large flood freq.	occ./yr	0.25	0.35	0.3	0	0.15
	Large flood riserate	m ³ /d	5.08	4.85	6.11		6.77
Large floods	Large flood fallrate	m ³ /d	1.72	2.38	2.39		2.37

SRES A1B scenario (comparable with RCP 6.0 DWD, 2018). With regards to use of EFCs in the region, Martínez-Capel et al., using two custom future scenarios, one of which incorporated both socio-economic growth trends as well as natural alterations, and the other of which only took into account climatic alterations, concluded that in both cases, runoff in the Zambezi-Chobe floodplains was likely to decrease. Similarly, they found an increase in both the magnitude and frequency of flow extremes, for the worst-case scenario, and a homogenisation of values for their less extreme ‘very likely’ scenario. Parallels can be drawn with the present results, in that under all RCP scenarios, extreme low flow events were longer and of greater magnitude, large flood events were of greater magnitude, and the naturally necessary small floods (World Bank, 2010) where less frequent, of smaller magnitude, and shorter duration.

There is no similar research regarding the use of IHAs/EFCs as input to a multicriteria decision analysis, hence the novelty of the present research. Due to this, a considerable amount of discussion concerning how the combination of IHA/EFCs and multicriteria decision analysis may be improved, is necessary. The discussion of key points arising from the current research is opened below.

4.1. A hydrological decision support system

Due to the exploratory nature of this research, there is bound to be much discussion upon its merits and failings. Prior to detailing them, it is important to clarify once more what the goal of the present multicriteria decision analysis is. Indeed, although most multicriteria decision analyses undertaken within the sphere of environmental resources management seek to incorporate a range of economic, social, and ecological criteria (SINTEF, 2013), the current analysis uses ecological criteria (derived from hydrological criteria) alone. That this results in large gaps in the decision support process is clear. For that reason, the

process presented here has been provided with the prefix ‘hydrological’, as it is first and foremost based upon, and used for, hydrological decision support. If, as is often the case with adaptive management projects and their necessarily iterative nature (Mimura et al., 2014), further information with a broader scope is available in the future, adapting the existing model in an iterative fashion so as to include such elements is likely to be easier than making an entirely new model. A future decision support system including further elements would then no longer be simply ‘hydrological’ in nature, but applicable more broadly, and thus, more representative of actual natural processes.

4.2. Validation

The multicriteria decision analysis undertaken here is based on the use of ‘dummy’ weight data. As such, the results of the MCDA have no current real-world use. Due to this, validation of the current results, in absolute terms, would be a pointless exercise. However, once real weights, derived from decision maker ‘preferences’ are obtained, validation of the results could then take place. The most powerful validation process would obviously be to compare the results of the IHA/EFC analysis, as well as the subsequent multicriteria decision analysis, with actual developments in the catchment over time, and the comparison of the multicriteria decision analysis results with the opinion of the stakeholders. However, the former is not feasible, and would, in addition, defeat the point of developing a decision support system to aid water resources management. As such, the remaining validation option, in the case of the hydrological decision support system presented here, is to present the results to the stakeholders in question, so as to determine if they agreed with the results generated. If so, then suitable resource management measures could then be implemented. As the current research stands, however, result validation is not possible, due to the use of ‘dummy’ weights.

Table 3

Weights and preference directions of all criteria, for each set of decision makers.

EFC	EFC indicator	Units	Weights, 0 - 1, sum of 1				Preference directions			
			Balanced	Inhabitants	MadMax	Waterworld	Balanced	Inhabitants	MadMax	Waterworld
Monthly flows	October	m ³ /d	0.03	0.05	0.03	0.04	Max	Max	Min	Max
	November	m ³ /d	0.03	0.05	0.03	0.04	Max	Max	Min	Max
	December	m ³ /d	0.03	0.05	0.03	0.04	Max	Max	Min	Max
	January	m ³ /d	0.03	0.05	0.03	0.04	Max	Max	Min	Max
	February	m ³ /d	0.03	0.05	0.03	0.04	Max	Max	Min	Max
	March	m ³ /d	0.03	0.05	0.03	0.04	Max	Max	Min	Max
	April	m ³ /d	0.03	0.05	0.03	0.04	Max	Max	Min	Max
	May	m ³ /d	0.03	0.05	0.03	0.04	Max	Max	Min	Max
	June	m ³ /d	0.03	0.05	0.03	0.04	Max	Max	Min	Max
	July	m ³ /d	0.03	0.05	0.03	0.04	Max	Max	Min	Max
Extreme low flows	August	m ³ /d	0.03	0.05	0.03	0.04	Max	Max	Min	Max
	September	m ³ /d	0.03	0.05	0.03	0.04	Max	Max	Min	Max
	Extreme low peak	m ³ /d	0.03	0.00	0.14	0.00	Max	Max	Min	Max
	Extreme low duration	days	0.03	0.00	0.14	0.00	Min	Min	Min	Min
High flow pulses	Extreme low timing	Julian date	0.03	0.00	0.14	0.00	Min	Min	Min	Min
	Extreme low freq.	occ./yr	0.03	0.00	0.14	0.00	Min	Min	Min	Min
	High flow peak	m ³ /d	0.03	0.03	0.00	0.02	Max	Max	Min	Max
	High flow duration	days	0.03	0.03	0.00	0.02	Max	Max	Min	Max
	High flow timing	Julian date	0.03	0.03	0.00	0.02	Max	Max	Min	Max
	High flow frequency	occ./yr	0.03	0.03	0.00	0.02	Max	Max	Min	Max
Small floods	High flow rise rate	m ³ /d	0.03	0.03	0.00	0.02	Min	Min	Min	Max
	High flow fall rate	m ³ /d	0.03	0.03	0.03	0.00	Min	Min	Max	Min
	Small Flood peak	m ³ /d	0.03	0.03	0.00	0.03	Min	Max	Min	Max
	Small Flood duration	days	0.03	0.03	0.00	0.03	Max	Max	Min	Max
	Small Flood timing	Julian date	0.03	0.03	0.00	0.03	Max	Min	Min	Max
	Small Flood freq.	occ./yr	0.03	0.03	0.00	0.03	Max	Max	Min	Max
Large floods	Small Flood riserate	m ³ /d	0.03	0.03	0.00	0.03	Min	Min	Min	Max
	Small Flood fallrate	m ³ /d	0.03	0.03	0.03	0.00	Min	Min	Max	Min
	Large flood peak	m ³ /d	0.03	0.00	0.00	0.04	Min	Min	Min	Max
	Large flood duration	days	0.03	0.00	0.00	0.04	Min	Min	Min	Max
	Large flood timing	Julian date	0.03	0.00	0.00	0.04	Min	Min	Min	Max
	Large flood freq.	occ./yr	0.03	0.00	0.00	0.04	Min	Min	Min	Max
	Large flood riserate	m ³ /d	0.03	0.00	0.00	0.04	Min	Min	Min	Max
	Large flood fallrate	m ³ /d	0.03	0.05	0.03	0.00	Min	Min	Max	Min

4.3. Weighting

Indeed, obtention and use of accurate, real world weights, on the other hand, is the next step in the present research. Indeed, weighting is a perennial issue in MCDA. How to obtain weights, when no decision maker input is available, is a very difficult question, with no correct answers. The simple process of weight elicitation requires numerous

subjective decisions to be taken. Here, hypothetical weights were used. Perhaps most controversial in this analysis, is the use of a weight of 0. This effectively rules out the contribution of a criteria to a preference value of an alternative. However, in view of the lack of any way to verify the outcomes of this analysis, the use of 0 as a weight was used, so as to allow a type of *reductio ad absurdum*, whereby the analysis provides output that makes sense given the input data. In this way,

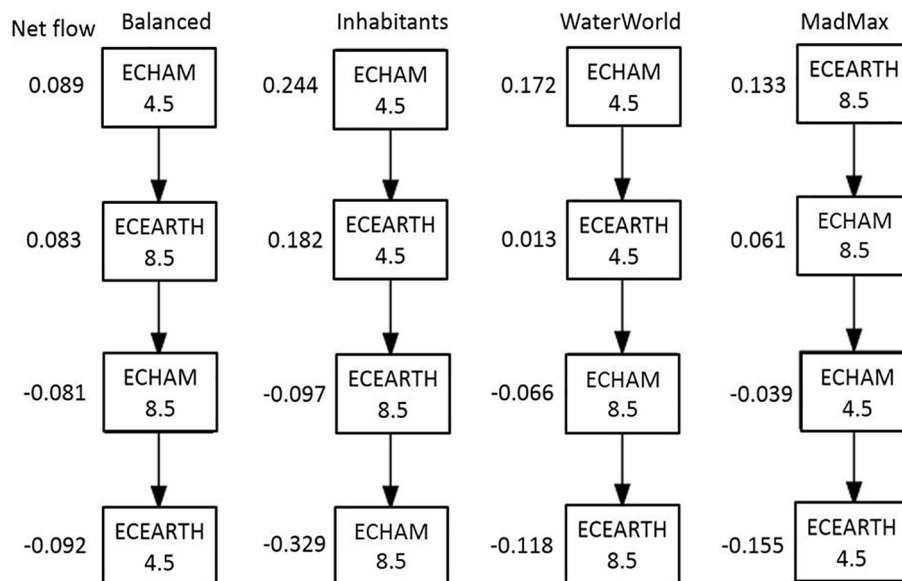


Fig. 3. Graphical output of the comparison of alternatives based upon the net flow values output by the Promethee II MCDA analysis. From left to right: the balanced, inhabitants, Water World, and Mad Max scenarios.

decision makers with a preference for very dry conditions obtained a ranking of alternatives placing the driest scenarios first. Similarly, the wetter scenarios were preferred by both the inhabitant and flood preference decision maker groups, as one might expect. Further work using real weights obtained from stakeholders in the catchment, is both necessary and highly desirable, in order to further advance the current research.

The current, initial analysis, is thus, primarily, a proof of concept. As stated previously, the multicriteria decision analysis undertaken here used the “equal weights method” as well as the application of hypothetical weights aimed at “covering a wide range of possible viewpoints” (Alvarez-Guerra et al., 2010). A useful approach is to then undertake stochastic analysis upon that set of weights, so as to evaluate the sensitivity of each criteria weight (e.g. Tervonen and Lahdelma, 2007). Alvarez-Guerra et al. (2010) undertook such an analysis using the Monte Carlo method, and this seems to be an interesting avenue for future research to take as well. However, one issue that may be encountered here could be obtaining the necessary evidence-based distribution required for a Monte Carlo simulation.

4.4. Socioeconomic assessment

Success in the current methodological exploration will also allow for integration of socioeconomic assessment, in the form of proxies such as land use scenarios or integration of Shared Socioeconomic Pathway (SSP) data, so as to complement the representative concentration pathway datasets already used. Jeong et al. (2014), for example, made use of indicators of hydrologic analysis to undertake an assessment of the effects of urbanization and climate change on stream health in a watershed. Regarding SSPs, Van Ruijven et al. (2013) state that inclusion of the parallel RCP and SSP scenarios to impacts, adaptation, and vulnerability analysis will “provide a range of new opportunities for integrating alternative socioeconomic and climatic futures for the purposes of local, regional, or sectoral impact analyses and for evaluating possible adaptation and mitigation policies”. They further recognise that, much as RCPs are required to be downscaled for sub-global scale analysis, SSPs are likely to be required to undergo a similar downscaling process. Related to this, the use of shared socioeconomic pathways in sub-global resources management has already been undertaken in various ways. Absar and Preston (2015), for example, have explored how SSPs might be extended for sub-national impacts, adaptation, and vulnerability studies, and provide a framework methodology involving scenario nesting according to data scale and theme.

In specific relation to water, Hanasaki et al. (2013) assessed global water scarcity using shared socioeconomic pathways. More generally, Wada et al. (2016) stated that “most [water model] studies have focussed on historical reconstruction of global water use for model validation, and so far very few assessments have been built on the shared socio-economic pathways (SSPs) and the representative concentration pathways (RCPs) in combination to evaluate the impacts of global change on water resources”. The fact that such combined RPC/SSP scenarios have not been undertaken to a large degree on a global scale, yet alone a regional or watershed scale, indicates that the goals of the present decision support system are ambitious, necessary, and, as yet, not widespread in the research community. Developing a successful decision support system incorporating both representative concentration pathway and shared socioeconomic pathway data, or, at least, elements thereof, would therefore be a significant contribution to water modelling and integrated water resources management research.

4.5. Potential for spatial analysis

The present research also has some potential for contributing to spatial analysis of runoff within the catchment, and thus, too, to spatial planning activities. Due to the use of the J2000 model, a distributed hydrological model, the multicriteria decision analysis undertaken here

could be undertaken on each subunit used within the analysis. These could be pixels, if the model is raster based, or, as in the J2000 model used here, hydrological response units. In such a way, for each spatial unit for which model results are obtained, one might be able to say that a certain scenario may better suit the requirements of that catchment. In the case of the present research, these ‘requirements’ are stated in the form of preferred hydro-ecological values. However, if one is able to draw a link between a set of environmental flow components and other aspects of the catchment, one could assess other spheres of the area in question as well. King et al. (2003), for example, propose a holistic method requiring the assessment of the socio-economic impact engendered by a change in environmental indicator. Granted, such an assessment is greatly more time consuming than the desktop-based analysis (Tharme, 2003) undertaken here. Nonetheless, if the required resources for such an analysis are available or can be obtained, such an analysis should be undertaken, so as to provide decision makers with as great a range of information regarding consequences of alterations in the catchment, as possible.

4.6. Uncertainty

It is clear that in complex decision making processes, involving complex, but imperfect, and often competing, models, as well as uncertain input data, error propagation becomes an ever greater issue, meaning uncertainty analysis becomes ever more important. Such an analysis has not yet been undertaken in the present research. The climate data driving the hydrological model were subject to bias correction, and potential sources of uncertainty affecting the modelling process and results, ranging from data reliability and scarcity to sources of error inherent to the model used, have been discussed and enumerated at length in Meinhardt (2017). Key sources of uncertainty related to the present research that are yet to be assessed are sources of uncertainty relating to indicator redundancy and inter-correlation (Olden and Poff, 2003; Gao et al., 2009), and multicriteria decision analysis (Hyde, 2006; Scholten et al., 2015; Groothuis-Oudshoorn et al., 2017) and Promethee in particular (Hyde et al., 2003). Future work will aim to assess uncertainty at each step of the process undertaken, as well as potential sources of error in the data used.

5. Conclusion

The present hydrological multicriteria decision analysis is developed to analyse the degree of change a group of scenarios results in, in terms not only of overall water balance and timing, but also flow component timing, frequency, and rise and fall rate. This was undertaken using open-source (J2000 and diviz) and free to use (Indicators of Hydrologic Alteration) software. Hydrological modelling output was fed into the IHA program, from which environmental flow component values were obtained, which were in turn used as criteria performance values in the outranking multicriteria decision analysis using the Promethee method. The results were in line with what one might expect, given the researcher-defined hypothetical weights used, and confirm that the method acts as one would expect it to. Admittedly, a user could undertake such an analysis without using software such as the IHA program, but it may well prove to be more costly in terms of both time and resources. Using the hydrologic alteration values, it may be possible to determine which indicators of hydrologic alteration, and thus, which linked environmental flow components, may be the greatest drivers of change in a given flow dynamic post-impact, or under conditions created by a specific scenario. Thus, the idea presented here, consisting of applying the environmental flow component values as performance values in a multicriteria decision analysis, permits the user to determine, depending on which environmental flow components they value most, or would most prefer to keep at a certain level in the future according to their priorities, which scenario and which balance of environmental flow components would best meet

their need. Expanding the type of indicators used outside of the ecological sphere simply requires the user to draw a robust link between an environmental flow component and a factor of interest. Future work consists of integrating weights elicited from expert judgement and review of previous relevant studies, automation of the process to the greatest degree possible, integration with a web-based platform, and, if possible, inclusion of socioeconomic scenarios, ideally using SSPs, so as to complement the RCPs already used.

Acknowledgements

The authors acknowledge the support of the German Federal Ministry of Education and Research which funded this research within scope of the “SASSCAL” initiative (grant number 01LG1201E).

References

- Absar, M., Preston, B.L., 2015. Extending the shared socioeconomic pathways for sub-national impacts, adaptation, and vulnerability studies. *Global Environ. Change*. <http://dx.doi.org/10.1016/j.gloenvcha.2015.04.004>.
- Alvarez-Guerra, M., Canis, L., Voulvoulis, N., Viguri, J.R., Linkov, I., 2010. Prioritization of sediment management alternatives using stochastic multicriteria acceptability analysis. *Sci. Total Environ.* 408 (20), 4354–4367. <http://dx.doi.org/10.1016/j.scitotenv.2010.07.016>.
- Arthington, A.H., Bunn, S.E., LeRoy Poff, N., Naiman, R.J., 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecol. Appl.* 16 (4), 1311–1318.
- Bezhadian, M., Kazemzadeh, R.B., Albadvi, A., Aghdasi, M., 2010. PROMETHEE: a comprehensive literature review on methodologies and applications. *Eur. J. Oper. Res.* 2010, 198–215.
- Bigaret, S., Meyer, P., 2015. Illustrating the support of the MCDA process by the diviz workbench. In: Bisdorff, R., Dias, L., Meyer, P., Mousseau, V., Pirlot, M. (Eds.), *Evaluation and Decision Models with Multiple Criteria: Case Studies*. International Handbooks on Information Systems 978-3-662-46815-9, .
- Brakenridge, G.B., n.d. “Global Active Archive of Large Flood Events”, Dartmouth Flood Observatory, University of Colorado, <http://floodobservatory.colorado.edu/Archives/index.html> (accessed 19 December 2016).
- Brans, J.P., Vincke, Ph., 1985. Note—a preference ranking organisation method. *Manage. Sci.* 31 (6), 647–656. <http://dx.doi.org/10.1287/mnsc.31.6.647>.
- Brans, J.P., Vincke, Ph., Mareschal, B., 1986. How to select and rank projects: the PROMETHEE method. *Eur. J. Oper. Res.* 24, 228–238 Noord Holland.
- Convertino, M., Baker, K.M., Vogel, J.T., Lu, C., Suedel, B., Linkov, I., 2013. Multi-criteria decision analysis to select metrics for design and monitoring of sustainable ecosystem restorations. *Ecol. Indic.* 26, 76–86. <http://dx.doi.org/10.1016/j.ecolind.2012.10.005>.
- De Keyser, W., Peeters, P., 1996. A note on the use of PROMETHEE multicriteria methods. *Eur. J. Oper. Res.* 89 (1996), 457–461.
- De Smet, Y., Lidouh, K., 2013. An introduction to multicriteria decision aid: the PROMETHEE and GAIA methods. In: Aufaure, M.-A., Zimányi, E. (Eds.), *eBISS 2012, Lecture Notes in Business Information Processing* 138, pp. 150–176.
- Deutsche Wetter Dienst, 2018. <https://www.dwd.de/DE/klimawandel/klimawandel/klimaszenarien/rcp-szenarien.html> (accessed 21 January 2018).
- Diaby, V., Sanoga, V., Moussa, K.R., 2016. ELICIT: an alternative imprecise weight elicitation technique for use in multi-criteria decision analysis for healthcare. *Exp. Rev. Pharmacoecon. Outcomes Res.* 16 (1), 141–147. <http://dx.doi.org/10.1586/14737167.2015.1083863>.
- Dyer, F., ElSawa, S., Croke, B., Griffiths, R., Harrison, E., Lucena-Moya, P., Jakeman, A., 2014. The effects of climate change on ecologically-relevant flow regime and water quality attributes. *Stochastic Environ. Res. Risk Assess.* 28, 67–82. <http://dx.doi.org/10.1007/s00477-013-0744-8>.
- Figueira, J., Greco, S., Ehrgott, M. (Eds.), 2005. *Multi Criteria Decision Analysis: State of the Art Surveys*. Springer, New York.
- Fischer, C., Kralisch, S., Krause, P., Fink, M., Flügel, W.-A., 2009. Calibration of hydrological model parameters with the JAMS framework. in: *Proceedings of the 18th World IMACS/MODSIM Congress*, Cairns, Australia 13–17 July 2009.
- Francq, P., 2004. PROMETHEE, Orléans Institute: <http://www.otlet-institute.org/wikis/PROMETHEE.html> (accessed 18 November 2016).
- Gao, Y., Vogel, R.M., Kroll, C.N., LeRoy Poff, N., Olden, J.D., 2009. Development of representative indicators of hydrologic alteration. *J. Hydrol.* 374, 136–147.
- Georgakakos, A.P., 2006. *Decision Support Systems for Water Resources Management: Nile Basin Applications and Further Needs*, Atlanta, Ga, pp. 1–22.
- Groothuis-Oudshoorn, C.G.M., Broekhuizen, H., van Til, J., 2017. Dealing with uncertainty in the analysis and reporting of MCDA. In: Marsh, K., Goetghebeur, M., Thokala, P., Baltussen, R. (Eds.), *Multi-Criteria Decision Analysis to Support Healthcare Decisions*, pp. 67–85. <http://dx.doi.org/10.1007/978-3-319-47540-0>.
- Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y., Hijioka, Y., Kainuma, M., Kanamori, Y., Masui, T., Takahashi, K., Kanae, S., 2013. A global water scarcity assessment under shared socio-economic pathways – Part 1: water use. *Hydrol. Earth Syst. Sci.* 17 (7), 2375–2391. <http://dx.doi.org/10.5194/hess-17-2375-2013>.
- Helmschrot, J., Kralisch, S., Quintino, M., Masamba, W., Steudel, T., Göhmann, H., Zander, F., Ambrosio, N., Baumberg, V., Mosimanyana, E., Homolka, A., Mwewa, L., Mashauri, D.-A., Flügel, W.-A., 2014. Environmental information management and hydrological system modelling for the assessment of hydrological ecosystem functions and services (ESF/ESS) in the Okavango River Basin. *Zbl. Geol. Paläont. Teil I* 2014 (1). <http://dx.doi.org/10.1127/zgpl/2014/0000-0000>.
- Henriksen, J.A., Heasley, J., Kennen, J.G., Niewsand, S., 2006. *Users' Manual for the Hydroecological Integrity Assessment Process Software (Including the New Jersey Assessment Tools)*. U.S. Geological Survey, Biological Resources Discipline, pp. 71 Open File Report 2006-1093.
- Hyde, K., Maier, H.R., Colby, C., 2003. Incorporating uncertainty in the PROMETHEE MCDA method. *J. Multi-Criteria Decis. Anal.* 12, 245–259. <http://dx.doi.org/10.1002/mcda.361>.
- Hyde, K., 2006. *Uncertainty Analysis Methods for Multi-Criteria Decision Analysis*. (Ph.D. Thesis).
- Ishizaka, A., Nemery, P., 2013. *Multi-criteria Decision analysis – Methods and Software*.
- Jeong, J., Kannan, N., Arnold, J.G., 2014. Effects of urbanization and climate change on stream health in north-central Texas. *J. Environ. Qual.* 43 (1), 100–109. <http://dx.doi.org/10.2134/jeq2011.0345>.
- King, J., Brown, C., Sabet, H., 2003. A scenario-based approach to environmental flow assessments for rivers. *River Res. Appl.* 19, 619–639. <http://dx.doi.org/10.1002/rra.709>.
- Kling, H., Stanzel, P., Preishuber, M., 2014. Impact modelling of water resources development and climate scenarios on Zambezi River discharge. *J. Hydrol.: Reg. Stud.* 1 (2014), 17–43.
- Krause, P., 2001. *Das hydrologische Modellsystem J2000 – Beschreibung und Anwendung in groen Flugebieten*. Schriften des Forschungszentrum Jülich, Reihe Umwelt/Environment Band 29.
- Krause, P., 2002. Quantifying the impact of land use changes on the water balance of large catchments using the J2000 model. *Phys. Chem. Earth* 27, 663–673.
- Magilligan, F.J., Nislow, K.H., 2005. Changes in hydrologic regime by dams. *Geomorphology* 71, 61–78. <http://dx.doi.org/10.1016/j.geomorph.2004.08.017>.
- Maingi, J.K., Marsh, S.E., 2002. Quantifying hydrologic impacts following dam construction along the Tana River, Kenya. *J. Arid Environ.* 50, 53–79. <http://dx.doi.org/10.1006/jare.2000.0860>.
- Martin, D.M., Labadie, J.W., LeRoy Poff, N., 2015. Incorporating social preferences into the ecological limits of hydrologic alteration (ELOHA): a case study in the Yampa-White River basin, Colorado. *Freshwater Biol.* 60, 1890–1900. <http://dx.doi.org/10.1111/fwb.12619>.
- Martínez-Capel, F., Garía-Lopez, L., Beyer, M., 2016. Integrating hydrological modelling and ecosystem functioning for environmental flows in climate change scenarios in the Zambezi River (Zambezi Region, Namibia). *River Res. Appl.* 33 (2), 258–275.
- Maystre, L.Y., Pictet, J., Simos, J. (Eds.), 1994. *Méthodes multicritères ELECTRE*. In: *Presses Polytechniques et Universitaires Romandes*, Lausanne.
- Meinhardt, M., 2017. *Auswirkungen des Klimawandels auf die Hydrologie im Oberen Zambezi: Ein prozessbasierter räumlich distributiver Modellierungsansatz zur Quantifizierung der hydrologischen Veränderungen unter Berücksichtigung der jährlichen Überflutung*. (Ph.D. Dissertation).
- Mimura, N., Pulwarty, R.S., Duc, D.M., Elshinnawy, I., Redsteer, M.H., Huang, H.Q., Nkem, J.N., Sanchez Rodriguez, R.A., 2014. Adaptation planning and implementation. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 869–898.
- Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J., Urquhart, P., 2014. Africa. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199–1265.
- Olden, J.D., Poff, N.L., 2003. Redundancy and the choice of hydrological indices for characterizing streamflow regimes. *River Res. Appl.* 19 (2), 101–121. <http://dx.doi.org/10.1002/rra.700>.
- Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.R., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C., Henriksen, J., Jacobson, R.B., Kennen, J.G., Merritt, D.M., O'Keefe, J.H., Olden, J.D., Rogers, J.H., Thorne, R.E., Warner, A., 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biol.* 55, 147–170. <http://dx.doi.org/10.1111/j.1365-2427.2009.02204.x>.
- Poff, N.L., Zimmerman, J.K.H., 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biol.* 55, 194–205. <http://dx.doi.org/10.1111/j.1365-2427.2009.02272.x>.
- Porse, E.C., Sandoval-Solis, S., Lane, B.A., 2015. Integrating environmental flows into multi-objective reservoir management for a transboundary, water-scarce River Basin: Rio Grande/Bravo. *Water Resour. Manage.* 29 (8), 2471–2484. <http://dx.doi.org/10.1007/s11269-015-0952-8>.
- Ros, J.C., 2011. *Introduction to Decision Deck-Diviz: Examples and User Guide*.
- Roy, B., 1985. *Méthodologie Multicritère à la décision: Méthodes et cas*. In: *Économica*, Paris.
- Sadok, et al., 2008. Ex ante assessment of the sustainability of alternative cropping

- systems: implications for using multi-criteria decision-aid methods. A review. *Agron. Sustainable Dev.* 28 (1), 163–174 Springer Verlag/EDP Sciences/INRA.
- SARDC, 2015. The Status Report on Integrated Drought and Flood Mapping. ZAMCOM/SADC/SARDC.
- Scholten, L., Schuwirth, N., Reichert, P., Lienert, J., 2015. Tackling uncertainty in multi-criteria decision analysis – an application to water supply infrastructure planning. *Eur. J. Oper. Res.* 242, 243–260. <http://dx.doi.org/10.1016/j.ejor.2014.09.044>.
- Schulze, R.E., Pike, A., 2004. Development and Evaluation of an Installed Hydrological Modelling System. WRC Report No. 1155/1/04.
- Serdeczny, O., Adams, S., Baarsch, F., et al., 2016. Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Region. Environ. Change*. <http://dx.doi.org/10.1007/s10113-015-0910-2>.
- SINTEF, 2013. Multi-Criteria Analysis Applied to Environmental Impacts of Hydropower and Water Resources Regulation Projects.
- Sojka, M., Jaskula, J., Wicher-Dysarz, J., Dysarz, T., 2016. Assessment of dam construction impact on hydrological regime changes in lowland river – a case of study: the Stare Miasto Reservoir located on the Powa River. *J. Water Land Dev.* 30, 119–125. <http://dx.doi.org/10.1515/jwld-2016-0028>.
- Stagl, J.C., Hattermann, F.F., 2016. Impacts of climate change on riverine ecosystems: alterations of ecologically relevant flow dynamics in the Danube River and Its Major Tributaries. *Water* 8, 566. <http://dx.doi.org/10.3390/w8120566>.
- Tervonen, T., Lahdelma, R., 2007. Implementing stochastic multicriteria acceptability analysis. *Eur. J. Oper. Res.* 178 (2), 500–513. <http://dx.doi.org/10.1016/j.ejor.2005.12.037>.
- Tharme, R.E., 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Res. Appl.* 19, 397–441. <http://dx.doi.org/10.1002/rra.736>.
- The Global Water Partnership, 2013. The Role of Decision Support Systems and Models in Integrated River Basin Management – Technical Focus Paper.
- The Nature Conservancy, 2009. Indicators of Hydrologic Alteration Version 7.1 User's Manual.
- The World Bank, 2010. The Zambezi River Basin A Multi-Sector Investment Opportunities Analysis, vols. I–IV. World Bank, Washington D.C.
- Turcksin, L., Bernardini, A., Macharis, C., 2011. A combined AHP-PROMETHEE approach for selecting the most appropriate policy scenario to stimulate a clean vehicle fleet. *Proc. Social Behav. Sci.* 20 (2011), 954–965.
- Van Ruijven, B.J., Levy, M.A., Agrawal, A., Biermann, F., Birkmann, J., Carter, T.R., Ebi, K.L., Garschagen, M., Jones, B., Jones, R., Kemp-Benedict, E., Kok, M., Kok, K., Carmen Lemos, M., Lucas, P.L., Orlove, B., Pachauri, S., Parris, T.M., Patwardhan, A., Petersen, A., Preston, B.L., Ribot, J., Rothman, D.S., Schweizer, V.J., 2013. Enhancing the relevance of shared socioeconomic pathways for climate change impacts, adaptation and vulnerability research. *Clim. Change* 122 (3), 481–494. <http://dx.doi.org/10.1007/s10584-013-0931-0>.
- Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S., Satoh, Y., van Vliet, M.T.H., Yillia, P., Ringler, C., Burek, P., Wiberg, D., 2016. Modeling global water use for the 21st century: the water futures and solutions (WfS) initiative and its approaches. *Geosci. Model Dev.* 9 (1), 175–222. <http://dx.doi.org/10.5194/gmd-9-175-2016>.
- Yang, T., Zhang, Q., Chen, Y.D., Tao, X., Xu, C., Chen, X., 2008. A spatial assessment of hydrologic alteration caused by dam construction in the middle and lower Yellow River, China. *Hydrol. Process.* 22, 3829–3843. <http://dx.doi.org/10.1002/hyp.6993>.
- Zanakis, S.H., Solomon, A., Wishart, N., Dubish, S., 1998. Multi-attribute decision making: a simulation comparison of selection methods. *Eur. J. Oper. Res.* 107 (3), 507–529. [http://dx.doi.org/10.1016/S0377-2217\(97\)00147-1](http://dx.doi.org/10.1016/S0377-2217(97)00147-1).